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INTERNATIONAL ELECTRIC VEHICLE SYMPOSIUM & EXHIBITION
EVS 50th anniversary 1969-2019

Design, Production & Verification of a Switched-Reluctance Wheel Hub Drive Train for Battery Electric Vehicles

Technology
Arts Sciences
TH Köln

SR4Wheel

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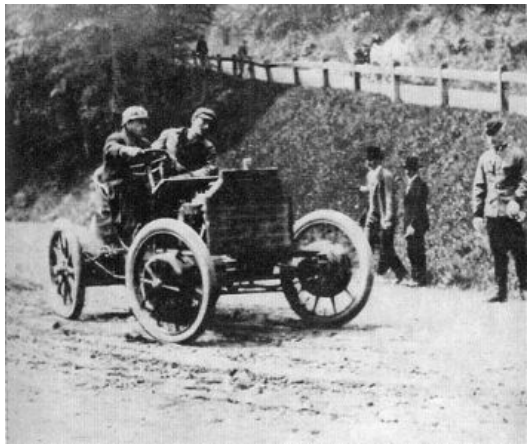
- Motivation & Project-Introduction
- Production & Test Bench Results 2nd Machine Design: Evolution 1
- Machine Design & Production 3rd Machine Design: Evolution 2
- Driving Test Results
  - NVH Optimization
  - Efficiency Optimization & NEDC Results
- Summary & Outlook

Motivation

modern BEV:

- „classic" single axle central motor drive
- permanent-magnet synchronous motor
- high vehicle costs

➢ low acceptance & interest



historical background (year 1900):

- gearless wheel hub motors
- DC-motor
- no friction brake included
- low power density
- high mass

Motivation

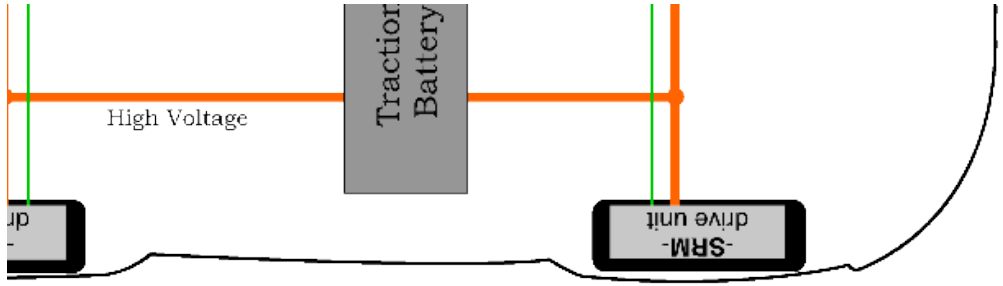
SR4Wheel:

- development of a single wheel drive
- based on a switched reluctance machine (SRM)
- integrated power electronics
- absolute identical installation space
- safe and redundant
- high efficiency
- low cost
- low weight

Why SRM?

- mechanical robust machine
- no permanent magnets
  - low cost, environment friendly and “price-stable”
  - no cogging torque

Motivation



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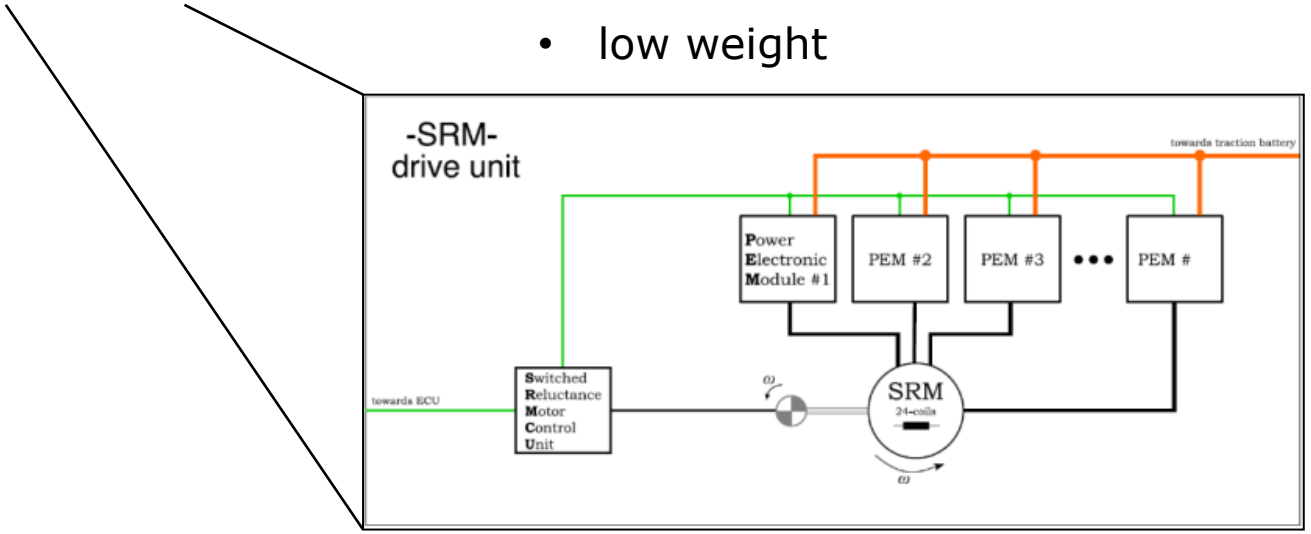

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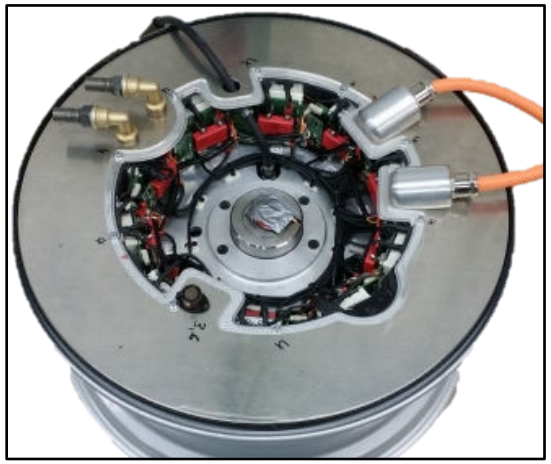
Production & Testing Evo 1

Based on the machine design shown at the EVS30 two fully usable prototypes had been built up using only internal resources of the university

The key characteristics of Evo 1 are:

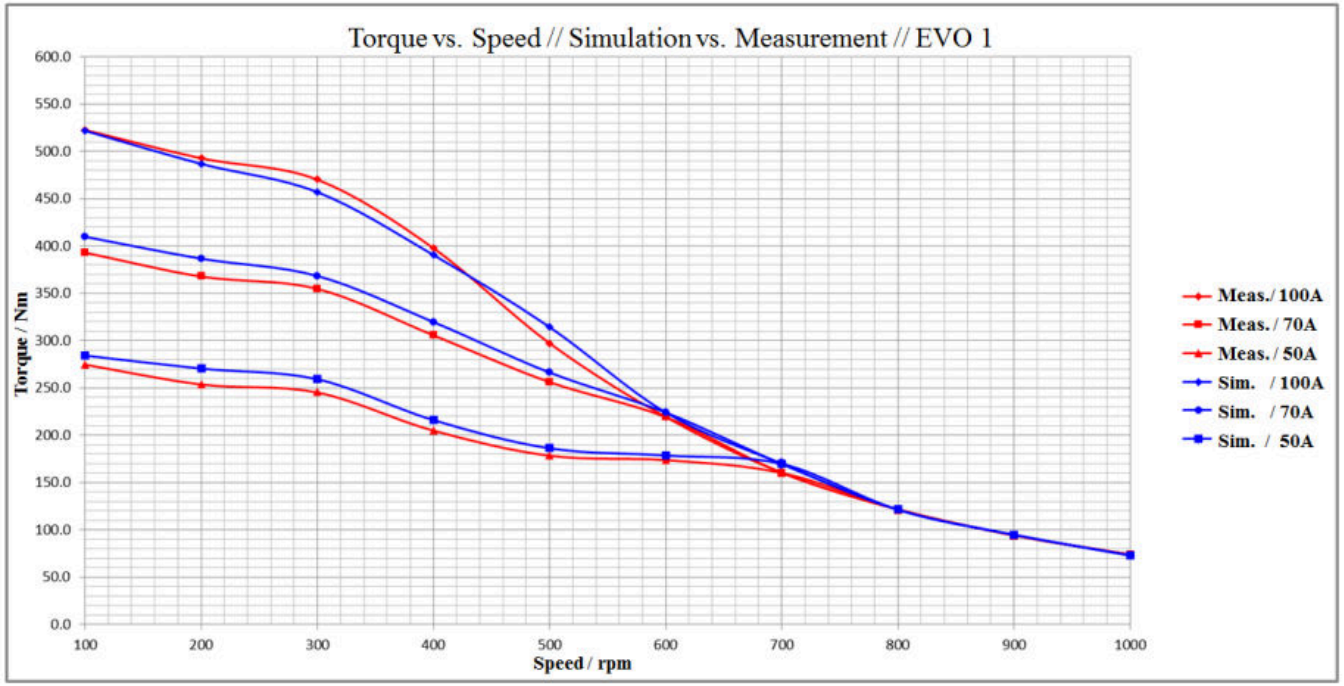
- Outer rotor SRM
- Neutral installation space
- Power electronics included
- Direct drive w/o gearbox



	Value	Unit
Type of Machine	SRM	-
Number of Phases	5	-
Number of Stator Teeth	20	-
Number of Rotor Teeth	24	-
Outer Diameter	430	mm
Active Length	100	mm
Number of Turns per Tooth	56	-
Air Gap	1	mm
Torque @ 0 rpm	520	Nm
Power @ 1400 rpm	60	kW
Weight	<50	kg
overall Efficiency	up to 90	%

Production & Testing Evo 1

- After performing several kinds of static and dynamic measurements with no load conditions, Evo 1 had been tested against a speed controlled ASM to analyse and optimize each single working point of the machine
- Running a conservative basic mapping (switch-on and off angles) could already fulfill the design goal of a launch torque >520Nm
- The comparison between 2D-FEA-Flux simulation and test-bench measurements could be validated with great confidence by a difference <5% in all working points



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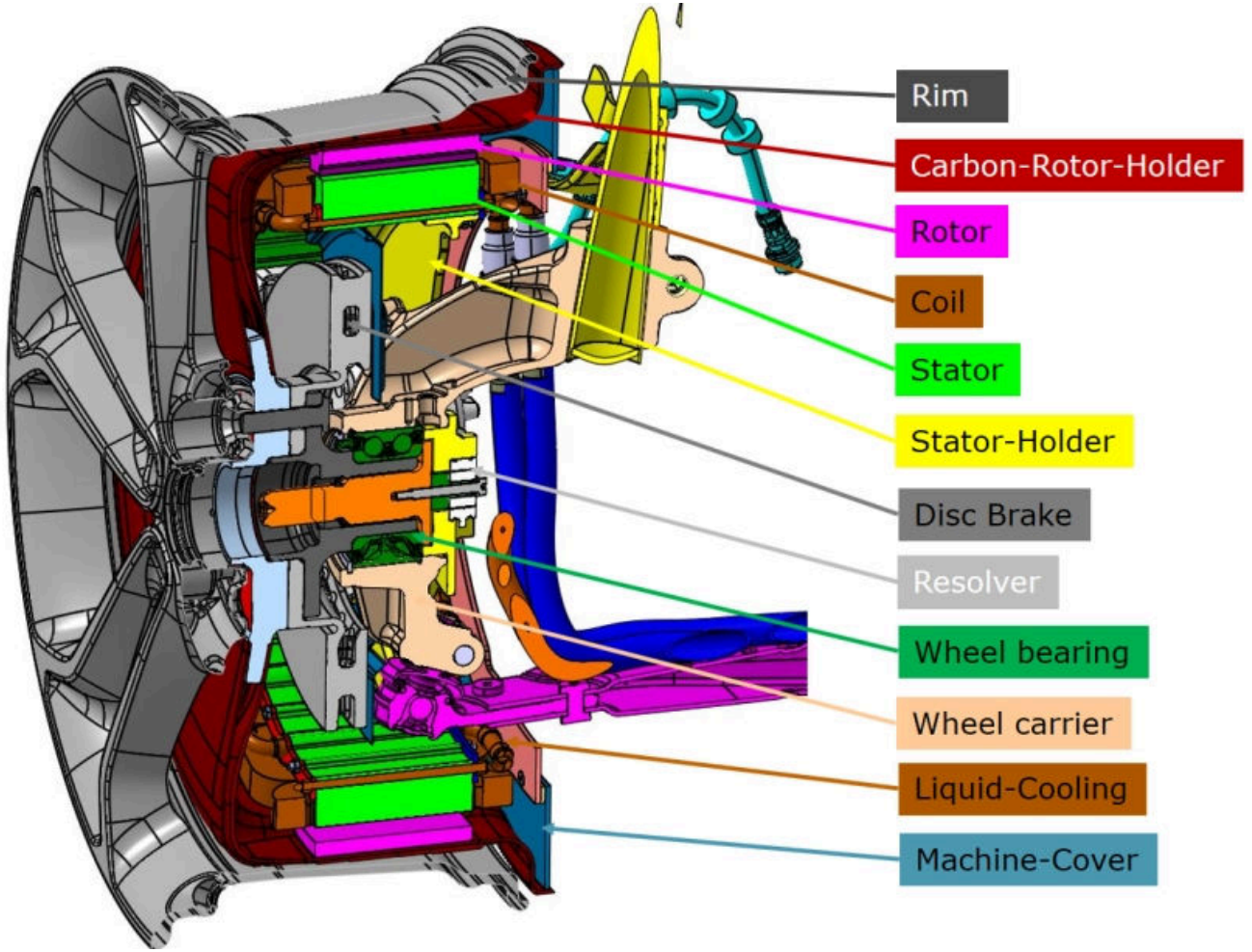
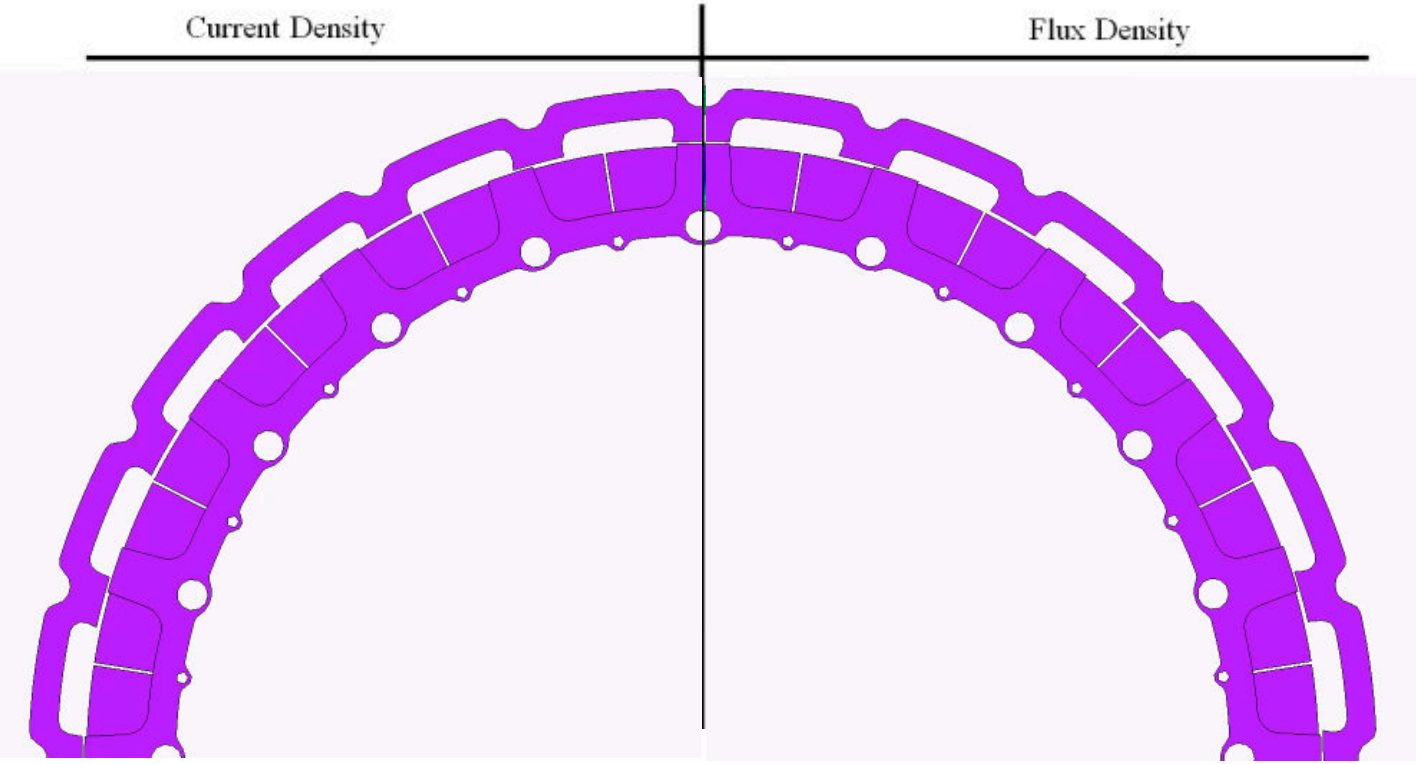
Machine Design & Production Evo 2

- On behalf of the experience made with Evo 1 on the test bench a final SRM Wheel Hub Motor for the front axle of the vehicle had been developed
- The original rim disc brake in the centre of the motor limits its radial installation space to 48mm, which is only 60% of Evo 1
- All moving parts like suspension and steering link had to be included what made the design process even more complicated
- The machine weight could be decreased by 22% compared to Evo1, by an increased power of 8%



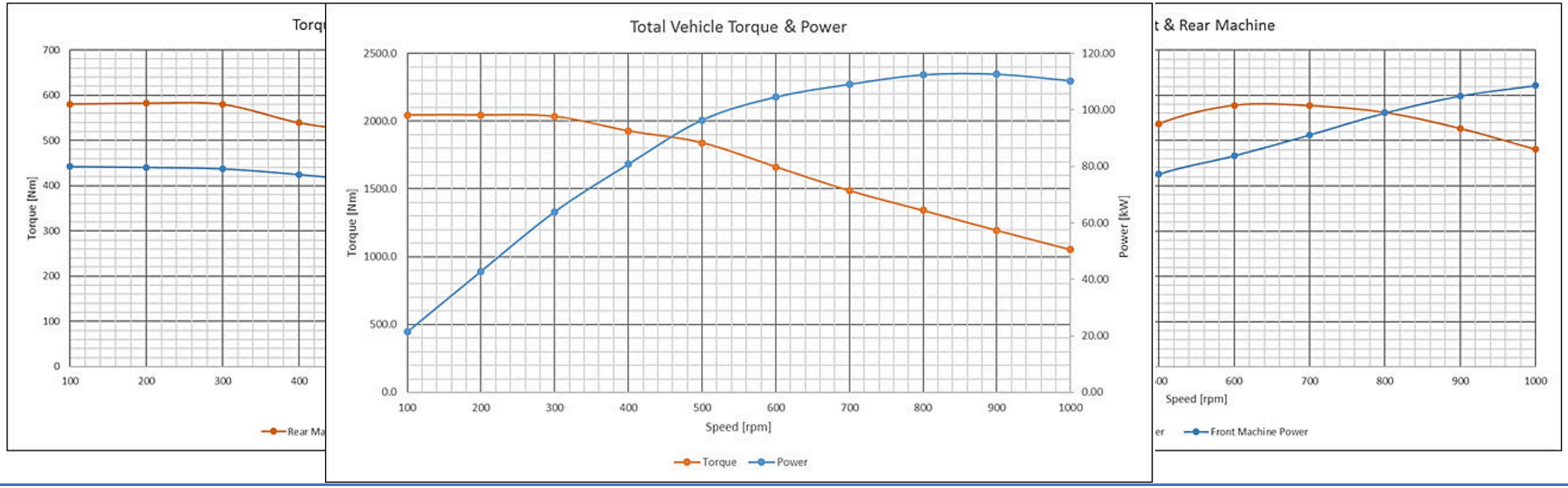
Machine Design & Production Evo 2

- Like its predecessor Evo 1, Evo 2 is a outer rotor, five phase machine, with short flux paths for high torque density and maximum efficiency
- By the integration of the liquid cooling system into the active material of the stator, even higher current densities at a stable thermal level could be reached



Machine Design & Production Evo 2

- The torque-speed characteristic of Evo 2 was designed to match the behaviour of Evo 1 on the rear axle
- Producing less launch torque at lower speeds (due to the limited installation space) Evo 2 can produce more power at higher speeds to compensate the power drop on the rear axle at >700rpm
- The result is a starting torque of >2000Nm and a constant power plateau of >100kW at >600rpm



Machine Design & Production Evo 2

- The final prototype machine Evo 2 made for the front axle of the project demonstrator:

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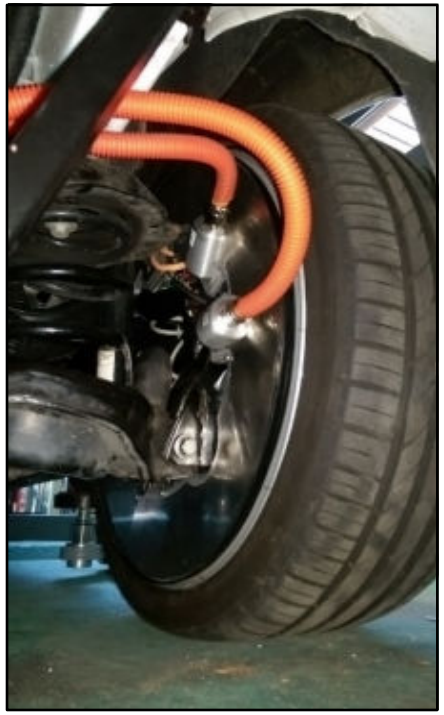
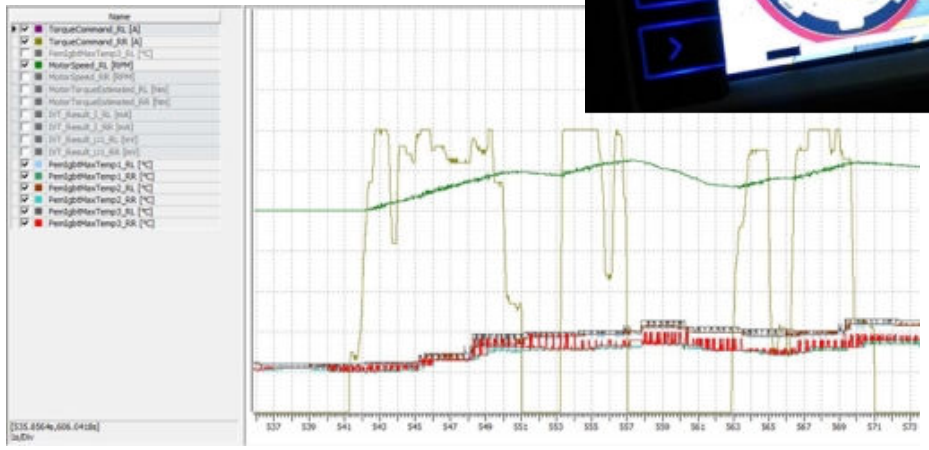
Driving Test Results

- The successful installation of all four machines, with a installation time of <1 hour per machine shows its great capabilities of retrofitting this machine into a given vehicle platform
- The project demonstrator vehicle (original Ford Focus Electric) had been equipped with an additional Control Unit to integrate the new drivetrain into the given software architecture
- A HMI displays all relevant values, can switch machine settings and logs all relevant parameters



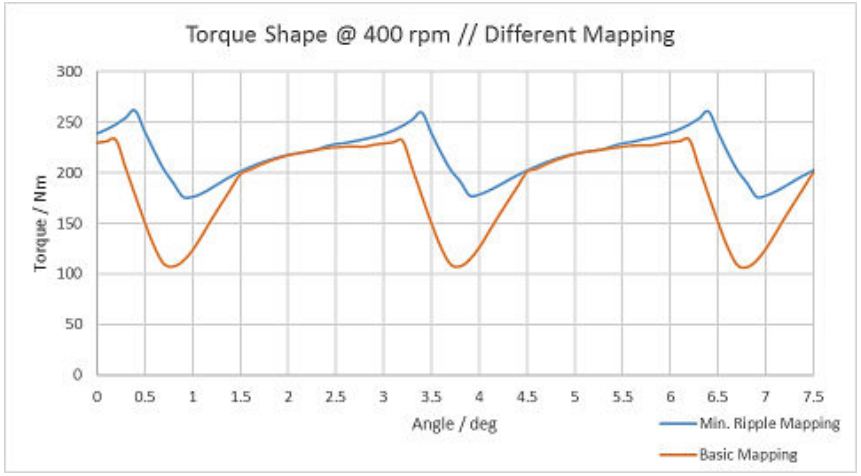


Driving Test Results

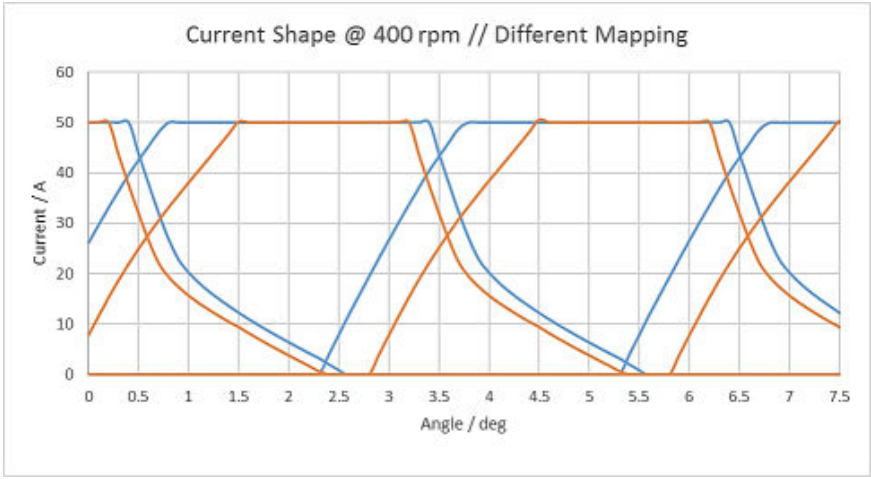
- Before testing the complete drivetrain on the road, several investigations had been performed on a self build 4WD roller test-bench inside the laboratory
- Main focus was placed on two natural disadvantages of the SRM, the NVH behaviour and the efficiency
- These two had been analysed and optimized in detail

NVH Optimization

- For a detailed view of the SRM Wheel Hub sound characteristics, audio recordings at various load points like *low speed / high torque* and *high speed / low torque* had been performed
- By analysing the emitted amplitudes separated into its frequencies over different motor speeds, critical speed ranges with high noise and vibration emission could be identified
- By analysing these motor speeds inside the FEA-simulation it turned out that higher torque ripples based on the chosen switch-on and switch-off parameter of each phase occurs at the given speed
- As a consequence, a new motor mapping with switching points for minimum torque ripple had been developed

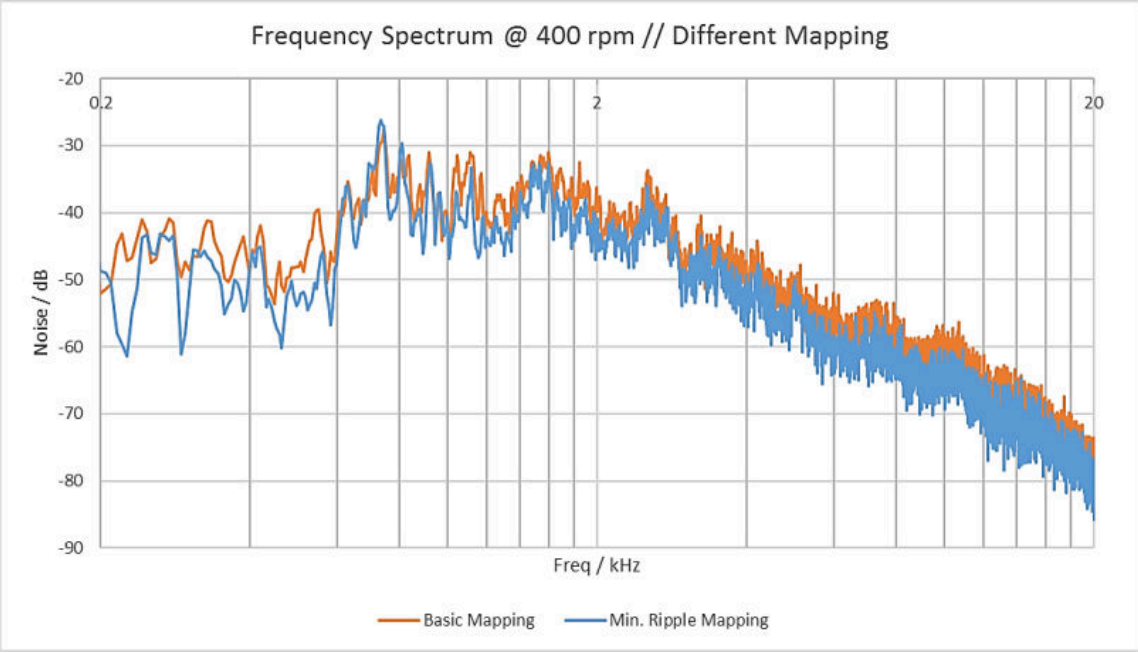


	Basic Map	Min. Ripple Map	Unit
Switch On Unaligned	0.5	0	deg
Switch Off Aligned	3.6	3.4	deg
Torque Ripple	54.2	32.6	%
Average Torque	191.4	219.4	Nm



NVH Optimization

- The direct connection between minimum torque ripple and reduced noise amplitude could be verified by repeatable measurement results on the test bench
- The example working point torque ripple reduction of >20% can reduce the noise level by -3.2 dB, and as a side effect increases torque by 14 %
- The new “NVH-friendly” machine map is stored inside die SRM Control Unit and can be activated via the bi-directional display

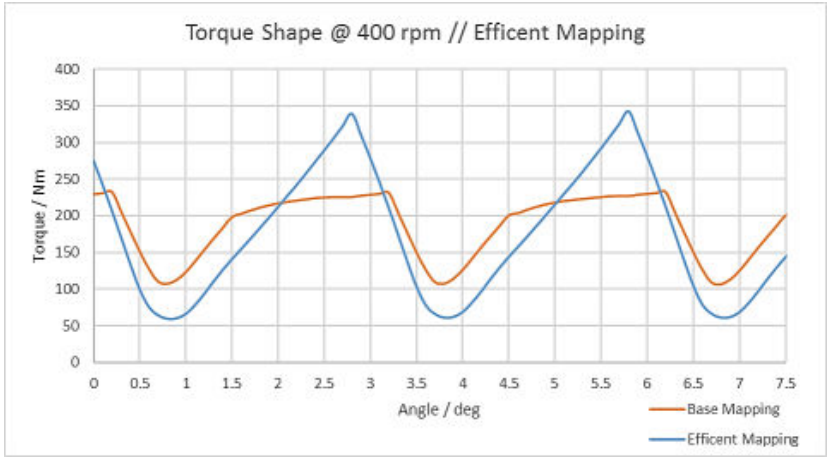


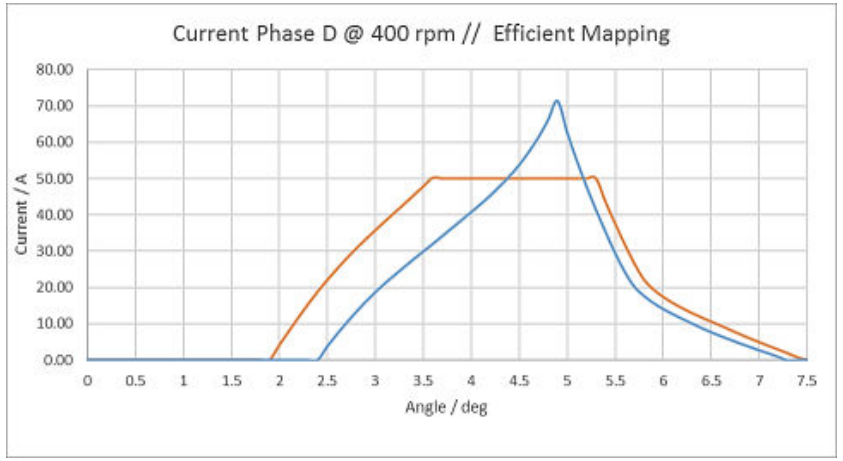
Efficiency Optimization

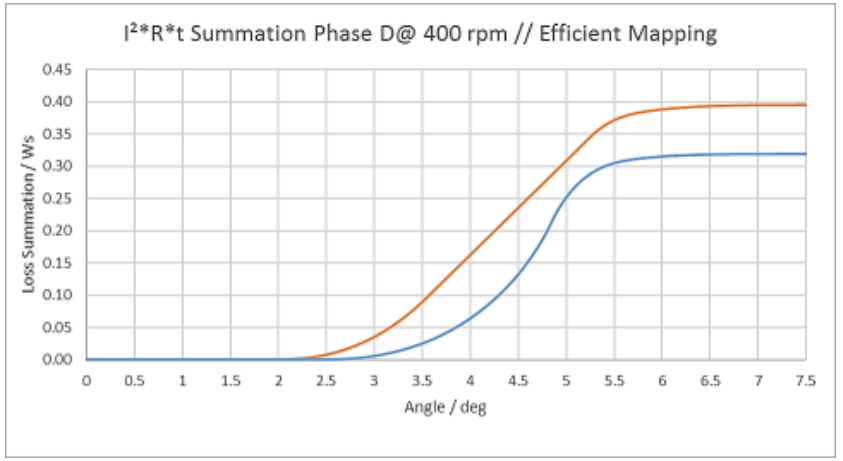
- When requesting a specific torque to accelerate the vehicle, from machine mapping point of view, there are three degrees of freedom:

  1. Switch On Phase *2.Switch Off Phase* *3. Current Amplitude*

- By the help of the FEA-calculation, the most efficient combination of these three parameters can be identified for each partial load point
- By tightening the "current window" but increasing the amplitude, the produced torque can be kept stable while decreasing the copper losses inside the Coil by 20 %
- This efficiency mode cannot fulfill the request for minimum torque ripple, a compromise between NVH and efficiency has to be identified

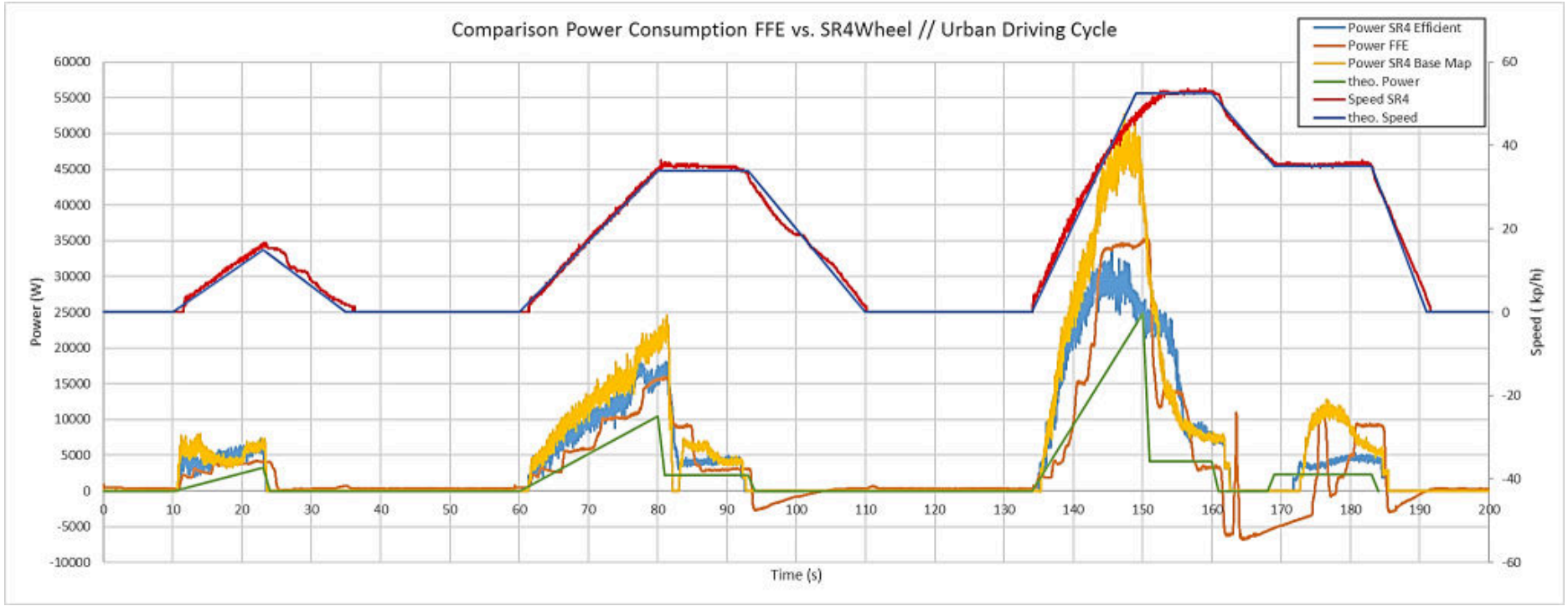






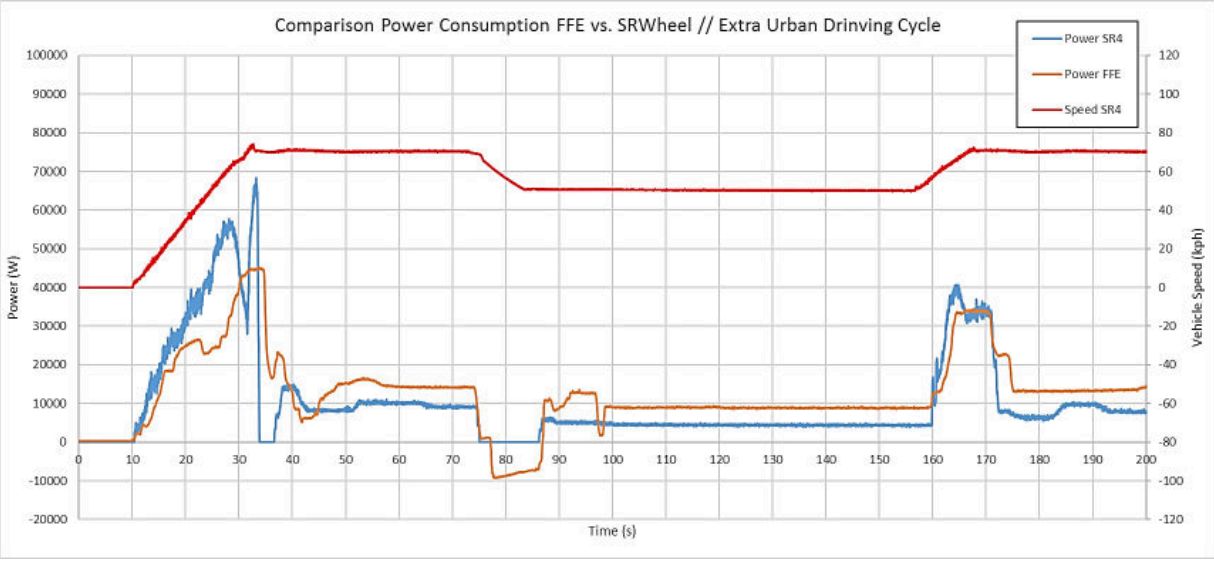
Efficiency Optimization

- Applying the gained knowledge to the complete torque-speed range of the SRM, a efficient optimized map can be produced and stored inside the Control Unit
- Running the NEDC with the complete vehicle on the 4WD roller test bench in standard map (yellow) as well as efficient map (blue) shows it great potential of energy saving, and close results to the original PSM (orange)



Efficiency Optimization

- A comparison between the original drivetrain, a single PSM (orange), and the newly four SRM wheel hub motors (blue) shows that a well suited and parametrised SRM is able to be competitive to the original drivetrain
- While the new SRM is more power consuming in acceleration phases, it can safe energy during steady state drives due to the lack of cogging torque as well as no gearbox and driveshaft losses
- The result is a NEDC consumption of 3.2 % more than the single PSM, **without using rare earth elements**



	SR4Wheel	Ford Focus w/o Recuperation	Unit
NEDC Distance	9,91	10,3	km
Energy consumption	2297,6	2313,5	Wh
Rated at 100 km	23,19	22,46	kWh / 100 km
Rated Energy Consumption	**103,2**	**100**	**%**

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Summary

- Two different evolution steps of an outer rotor SRM Wheel hub drive had been presented
- The machine can be installed at almost any vehicle platform with no changes to the suspension and brake system
- The system power of >100kW and the system torque of >2000Nm is sufficient for BEV's, the efficiency level is close to the original PSM drivetrain
- Due to no need of rare earth elements, the price forecast of this type of machine can be dedicated as stable and low-cost in the future
- A ready to drive prototype equipped with 4 machines had been build up and further NVH optimization is ongoing

Summary

- The short video gives an impression of first test drives with non optimized NVH-machine-mappings:

Q&A

Thanks a lot for your attention!

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Questions always welcome !